Acidic Precipitation in Ontario Study

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SUMMARY: SOURCE APPORTIONMENT ANALYSIS OF AIR AND PRECIPITATION DATA TO DETERMINE THE CONTRIBUTION OF THE SUDBURY SMELTERS TO ATMOSPHERIC DEPOSITION IN ONTARIO

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Synopsis

During the period from June 1982 to March 1983, there was a prolonged shutdown of the INCO and Falconbridge smelters at Sudbury, Ontario. Taking advantage of this opportunity, the Air Resources Branch of the Ontario Ministry of the Environment undertook a detailed analysis of the impact that these emission reductions had on the atmospheric deposition of acidity and sulfur oxides in Ontario.

This report summarizes the various meteorological analyses that were carried out in order to determine the contribution of the Sudbury smelters to atmospheric deposition in Ontario. The results, for various receptor areas, are given in Tables 2 and 5 (pp 15 and 18 respectively). For sulfates, the Sudbury contribution to the total wet deposition was typically less than 15%. Furthermore, the smelters were found to contribute on the order of 10-20% of the total dry deposition of sulfur compounds in central and northeastern Ontario, and less then 10% elsewhere.

BACKGROUND

During the period from June 1982 to March 1983, there was a prolonged shut-down of the INCO and Falconbridge Smelters at Sudbury, Ontario. The former smelter is one of the largest point sources of SO_2 emissions in North America, with annual emissions falling in the range of 500 to 800 thousand metric tons in recent years, and issuing mostly from a 381-metre "superstack". Falconbridge represents a considerably smaller source, with annual SO_2 emissions (mainly from a 93-metre stack) since 1978 being in the vicinity of 100 thousand tonnes. In view of the significant contribution of the Sudbury smelters to the total emissions of SO_2 in E.N. America, and especially in Ontario (see Figure 1), the Air Resources Branch of the Ontario Ministry of the Environment undertook a detailed analysis of the impact of these emission reductions on the atmospheric deposition of acidity and sulfur oxides in Ontario. The analysis also included selected nitrogen compounds and trace metals.

Previous work, carried out in the Sudbury basin itself, had shown that it would be difficult to detect changes in atmospheric deposition due to changes in smelter operations (Ontario Ministry of the Environment, 1979 ; Scheider et al., 1981). In fact, it has been estimated by aerometric analysis (Chan et al, 1984) that even within about 40 km of Sudbury, the smelters contribute on average only about 20% or less of the total wet deposition of most contaminants (including sulfur) found in precipitation, with the exception of Cu and Ni, where the smelters contribute about 70% of the total. The corresponding estimates for smelter contributions to the total dry deposition in the Sudbury basin were about 25% for S, about 60% for Cu and Ni, and less than 20% for most other trace metals. Long-range transport from sources to the south was identified as the major contributor to atmospheric deposition of sulfur and nitrogen oxides in the Sudbury basin.

The current analysis consisted largely of an examination of air and precipitation data collected during, and in the two years prior to, the smelter shut-down in 1982/83, in an attempt to quantify the

smelter contribution to wet and dry deposition at a number of receptors out to about 500 km from the source. Deposition maps and overall statistical comparisons were based on data from the Ministry's cumulative deposition network (Figure 2), which collects wet-only samples on a 28-day basis (these samples are analyzed for the major ions and a number of trace metals). More detailed trajectory and meteorological analyses were based on data from daily air and precipitation samplers operated in Ontario by the Ministry, the Atmospheric Environment Service, and Ontario Hydro (Figure 3). The air samples are analyzed for sulfates, nitrates, ammonium and SO_2. The daily precipitation samples are analyzed for the major ions.

DISCUSSION OF ANALYSES AND RESULTS

1. OVERALL NETWORK STATISTICS

Precipitation chemistry data obtained from stations within a radius of 250 km from Sudbury were grouped together on a seasonal basis (see, for example, Figures 4, 5 and 6). On these Figures, the year under each bar is shown first and the periods January to March, April to June, July to September and October to December are labelled as 02, 05, 08 and 11 respectively. Of particular interest was a comparison of the three shut-down periods (8208, 8211 and 8302) with the corresponding data collected during previous operating periods. This comparison was carried out for hydrogen ions, sulfates, nitrates and copper in precipitation. The only consistent decrease during the smelter shut-down was found for copper, which is a good tracer of smelter emissions (see Figure 5). This is also the only one of the parameters examined for which a median 2-sample test of significance indicated a decrease (at the 95% confidence level) for most seasons during the shut-down period. Nitrates (for which smelter emissions are small), were not significantly different during the shut-down and operating periods. Sulfates and hydrogen ions in precipitation showed no consistent, statistically significant decrease during the shut-down period.

2. PRECIPITATION AND WET DEPOSITION CONTOURS

Precipitation depth-weighted concentrations and wet deposition contours of the above four parameters were plotted for both the shut-down period and the corresponding operating periods. Figures 7 to 10 show ratios for SO_4 and Cu concentrations during the 82/83 shut-down period and the corresponding operating periods in 80/81 and 81/82. While for Cu there was a province-wide decrease in concentration during the shut-down period, SO_4 concentrations do not show a clear smelter effect. The pattern in the decrease of SO_4 concentrations during the shut-down period (Figures 7 and 8) resembles closely neither that for Cu (Figures 9 and 10) which is a good tracer for smelter emissions, nor that for NO_3 (Figures 11 and 12) which is not

emitted by smelters. The ratios shown in Figures 7 and 8 may be a resultant of both smelter emission changes, and a general decrease in SO_2 emissions from utilities in a number of states south of the Great Lakes during the study period, which amounted to more than one million tonnes on an annual basis (i.e. for 1982 as compared to 1980). Concentration contours for hydrogen ions did not display any readily recognizable patterns from which a smelter impact could be inferred. An examination of SO_4/NO_3 ratios, using NO_3 as a rough normalizing factor for meteorological variability (since nitrates are not emitted by the smelters), suggested an area of smelter influence extending out to 200 to 400 km from Sudbury. Since the use of nitrate as a normalizing factor can be questioned, however (it is subject to year-to-year emission variations and changes in chemical transformation rates), the above conclusions must be regarded as qualitative and suggestive only.

A comparison of wet deposition during the shut-down and operating periods proved even more difficult to interpret, since deposition is further complicated by year-to-year variations in the precipitation amount. Examples for SO_4 wet deposition are shown in Figures 13 and 14. The fact that the ratio of shut-down and operating period SO_4 deposition is less than unity to the east of Sudbury suggests a smelter effect. However, NO_3 deposition displays a similar phenomenon, suggesting that meteorological factors and/or changes in emissions in Southern Ontario and in states south of the Great Lakes may be largely responsible for these observations.

3. METEOROLOGICAL ANALYSIS OF DAILY PRECIPITATION AND AIR CONCENTRATION DATA

A more detailed analysis was carried out, based on both back-trajectories and a consideration of the synoptic meteorology associated with each sample, to select sub-sets of samples for operating and shut-down periods where the air parcels had previously passed over Sudbury. A comparison of air and precipitation concentrations and deposition during the operating and shut-down periods then permitted an estimate of the Sudbury smelter contribution

to atmospheric deposition at a number of receptor locations.

3.1 Precipitation Concentrations/Wet Deposition

3.1.1 Trajectory Analysis

For each of the six daily sampling sites shown in Figure 3, a "Sudbury sector" was defined as the octant of origin from the site which includes the Sudbury area. Surface geostrophic back-trajectories (with a frictional correction) were calculated from each site, the trajectory length being based on travel time of air parcels from the Sudbury area to the site. Thus, loading and concentration statistics for the Sudbury sector at Dorset were based on 6-hour northwesterly trajectories; for Longwoods, they were based on 12-hour northerly trajectories; for Railton, on 12-hour northwesterly trajectories; for Fernberg, on 24-hour easterly trajectories; and for Kapuskasing, on 12-hour south-southeast trajectories. The details of the trajectory calculation method and sector assignment are given by Kurtz (1983).

The results of this analysis are summarized in Table 1. As can be seen from this table, mean sulphate loadings did not appear to be depressed during the shut-down period at any of the sites (Table 1A). Loadings, in fact, varied in general with precipitation amount as a comparison of Tables 1A and 1C demonstrates. Mean sulphate concentrations, on the other hand, were typically lower at central, eastern and southeastern Ontario during the shut-down period.

Mean nitrate concentrations (Table 1B) in general were also low at central, eastern and southeastern Ontario during the shut-down period relative to values for the previous two years. The concentration reduction of nitrates cannot be attributed to the shut-down of the Sudbury sources, since the smelters are not significant emitters of nitrogen oxides.

Thus simple back-trajectory analysis gave inconclusive results regarding the impact of the smelters on wet deposition in Ontario.

The following section describes another approach which was attempted, to assign an upper bound to the smelter contribution at a number of receptor sites.

3.1.2 Classification by Synoptic Meteorological And Back-Trajectory Patterns

The validity of simple surface geostrophic or 850-mb trajectories to accurately represent air parcel origins during precipitation has been frequently challenged. Consequently, the following approach was taken: a study was made of the synoptic patterns accompanying each precipitation event at a given monitoring site. Cases were identified for which source assignment by back-trajectory analysis could be made with some confidence. For Dorset, for example, the post-cold front, pre-high pressure ridge situation was selected for further study (the significant synoptic pattern for a Sudbury impact varied from site to site, and for some sites several patterns were studied). This sub-set of samples was subjected to further stratification, by requiring that the envelope of 48-hour geostrophic back-trajectories (which are calculated every 6 hours during the period of interest) should include Sudbury and should at all times be within a prescribed sector (for the Dorset receptor, for example, this was the 90^{o} sector between west and north. In this way, we minimize the possibility of including cases where air parcels with recent history from the high emission density areas to the south of Dorset have entered the "Sudbury sector").

The above stratification scheme resulted in a small set of precipitation samples, for which a potential Sudbury smelter impact could be expected with a reasonable degree of confidence. For example, at Dorset, 9 such samples were identified during the July 80 - March 81 operating period ; 3 during the July 81 - March 82 operating period ; and 4 during the July 82 - March 83 shut-down period. (Figures 15 and 16 show the SO_4 and NO_3 concentrations in these samples). This sub-set was then subjected to further scrutiny, by applying the median 2-sample test of significance to the precipitation SO_4 and NO_3 concentrations. Only if the SO_4 concentrations during the shut-down period were significantly

different from those of the operating periods, while nitrate concentrations were not, did the analysis proceed further. Also, mean sulfate concentrations during the two operating periods had to be statistically the same.

While such a rigorous selection of events did result in a set of samples for which we could expect the smelter impact to be quantifiable by a comparison of operational and shut-down periods, several sites were eliminated due to insufficient data for a meaningful analysis, or because year-to-year changes in nitrate levels in the sample sub-set suggested the influence of source areas other than Sudbury. For the sites which were retained (Dorset, Railton and Chalk River), there was a further question to be addressed - viz. how to determine a representative Sudbury smelter contribution from such a small sub-set of data. The percentage of the total wet deposition associated with this sub-set was very small, and while we were reasonably confident of a potential Sudbury impact for this particular sub-set, there were clearly many other events and synoptic situations not included in the sub-set where the smelters were contributing to the sulfate deposition.

The approach finally taken was to determine a precipitation concentration difference (operating minus shut-down period values of concentration) for this sub-set, which was attributed to Sudbury smelters. Then the Sudbury contribution to the total deposition at each site was determined by multiplying the above precipitation concentration difference by the total precipitation depth accumulated over <u>all</u> events where Sudbury may have been affecting the receptor area. For Dorset, for example, <u>any</u> event where at least one surface back-trajectory during the sampling period was in the quadrant between west and north was included in the determination of the above total depth. As a result, estimates of the smelter contribution are probably near the <u>upper limit</u>, since the criteria on precipitation depth are very loose (obviously not <u>every</u> event at Dorset, for which at least one of the four back-trajectories during the sampling period is within the 90^{o} sector from west to north, will be influenced by Sudbury). However, since the sample size on which the source

apportionment estimates are based is small, and since scavenging efficiencies during the sub-set of precipitation events selected may not be representative of all events contributing to the wet deposition at the receptors of interest, caution is required here.

The results of this calculation are shown in Column 2 of Table 2. Out of interest, Column 3 also shows a rough upper limit estimate of the Sudbury contribution at Railton, Longwoods and Dorset based on simple back-trajectory analysis at these sites during the period from July 1980 to December 1981 (see Kurtz, 1983) when the smelters were in operation. The numbers shown in Column 3 represent the contribution to the total sulfate deposition, at each of the receptors, from three 45^{o} sectors (the Sudbury sector and the two adjacent sectors) and can, therefore, also be considered as near-upper limit estimates, since the total sector covers 135^{o} and sources within this sector other than Sudbury are also included.

The present analysis thus indicates that, for receptors out to about 400 km from the smelters, the smelter contribution to the wet sulfate deposition is expected to be less than about 10% to 15% of the total. This is in agreement with previous work done within the Sudbury basin (Chan et al., 1984) which indicated a long-term smelter contribution to the wet sulfate deposition on the order of 10% of the total. Further out from these sources, the contribution is expected to be even less. For purposes of reference, Figure 17 shows typical SO_4 wet deposition rates in Ontario. Application of the above results to other source and receptor areas is not straightforward, but in areas where the total deposition is higher, a source comparable in size to the smelters may contribute an even smaller percentage of the total. Consequently, source apportionment may prove to be an even more difficult task. It should be noted, however, that mathematical modelling suggests that the impact of the Sudbury smelters should be relatively larger in a northerly direction (due to meteorological factors). It is unfortunate, therefore, that the precipitation chemistry data set for Kapuskasing was inadequate for an analysis at this site.

3.2 Air Concentrations/Dry Deposition

To determine the impact of the Sudbury smelters on dry deposition in Ontario, air concentrations of sulfates, sulfur dioxide, nitrates and ammonia were compared during the shut-down and operating periods. We made the reasonable assumption that, if the same seasons for different years were compared, the change in the average dry deposition rate for a particular species would be proportional to the difference in its average air concentration during the two periods.

Daily air sample data were obtained from the stations shown in Figure 3. These included information on particulate sulfates, nitrates, and ammonia; nitric acid (sampled on nylon filter papers); and sulfur dioxide (sampled on filters impregnated with potassium carbonate). Two different approaches were used - one, a straightforward back-trajectory analysis; the other, a more detailed examination of trajectory and synoptic patterns, resulting in a subset of samples where the probability for a Sudbury impact was high. As in the case of the precipitation analysis, concentration differences attributable to Sudbury smelter operations were then used in the latter approach to estimate upper limits for the smelter impact on dry deposition at various receptor sites.

The method used for the back-trajectory analysis was the same as that described in Section 3.1.1. The results of this analysis are summarized in Table 3. Note that at all monitoring stations, mean sulfur dioxide concentrations within the Sudbury sector were depressed in the shut-down as compared to the operating period. Sulfate concentrations also decreased, except for the Longwoods and Fernberg sites. An example of SO_2 observations associated with air trajectories from the other sectors at Dorset, is shown in Table 4. Although there was a decrease in air concentrations within the other sectors as well during the smelter shut-down period, the change was most pronounced within the Sudbury sector (NW). The difference in mean SO_2 and SO_4 concentrations within the Sudbury sector during the smelter operating and shut-down periods was statistically significant at the 5% probability level, based on the median 2-sample test. For

nitrate, nitric acid and particulate ammonium, there was no significant difference.

The data in Table 3 were used (together with overall average air concentrations at each site and period of interest) to provide some preliminary estimates of the contribution of the Sudbury smelters to dry deposition of SO_2 and SO_4. These are shown in Table 5 (Column 3).

The more detailed meteorological analysis proceeded along similar lines to what was done with the precipitation data (see Section 3.1.2), except that the smelter influence was generally more pronounced in the SO_2 and SO_4 air concentration data than in the precipitation data, and the number of samples available for assessing the smelter contribution was consequently larger. First, a sub-set of samples was selected based on a careful examination of the synoptic meteorology, 48-hour back-trajectories, and tests of statistical significance for sulfur dioxide, sulfate and nitrate concentrations collected during the operating and shut-down periods (see Figure 18, for example, for SO_2 at Dorset within this sub-set). The contribution of the Sudbury smelters to the air concentration was calculated for this sub-set, and was assumed to be representative of <u>all</u> air parcels coming to the receptor from a 90^0-wide sector centred on Sudbury. The results, which are thought to be upper limits for the smelter contribution, are shown in Column 4 of Table 5. Note that the smelter impact is much more pronounced for SO_2 than for SO_4. Because most of the sulfur is emitted as SO_2 and because of the slow chemical conversion rates which have been observed in the smelter plume (typically less than 1% h^{-1}), this is not surprising. Much of the SO_2 would remain unconverted at the time of arrival at the receptors studied here.

SUMMARY AND RECOMMENDATIONS

A source apportionment analysis was carried out to determine the contribution to dry and wet deposition at various receptors in Ontario, due to emissions from two large smelters at Sudbury. The experiment involved was of the "direct emission change" type, and took advantage of a prolonged smelter shut-down during the latter half of 1982 and first quarter of 1983. Attention was focussed mainly on the sulfur oxides, which are thought to be the most important contributors to acid deposition.

Despite the fact that the smelter shut-down resulted in a 60% decrease in the provincial SO_2 emissions, quantification of the smelter impact on sulfur wet deposition proved to be a difficult task, due to the very large meteorological variability in the precipitation chemistry and wet deposition data, and the fact that the smelter contribution constitutes only 10% to 15% or less of the total at the receptors studied (these extended out to about 500 km from the source area). A statistical analysis of measurements within 250 km of the sources and an examination of the precipitation chemistry and wet deposition contours during the shut-down and operating periods failed to reveal any changes which could be clearly attributed to the smelters. Trajectory analysis also gave inconclusive results, with deposition from the Sudbury sector being dominated by variations in the precipitation amount, although at several receptor sites sulfate concentrations in the Sudbury sector did decrease during the smelter shut-down period. A more detailed meteorological analysis (involving an examination of both back-trajectories and the overall synoptic conditions accompanying each event) allowed a determination of the smelter contribution to wet deposition which is felt to approximate an upper limit and which was in rough agreement with similar upper estimates based on a simple trajectory analysis.

Changes in air concentrations and, therefore, dry deposition proved easier to detect. Generally, there was a readily detectable decrease in the average SO_2 levels within the Sudbury sector during the shut-down period. Changes in airborne sulfates were more

difficult to quantify. Although application of the present results to other sources and receptor areas is not straightforward, they do suggest that it will be easier to apportion the contribution of a similar source (or source area) to dry deposition than to wet deposition.

On the basis of past experience with the Sudbury smelters, source apportionment based on direct emission changes at one or two large point sources is not recommended. It would seem that, only if there are emission changes in a particular source area on the order of a million tonnes of SO_2 per year or more, would there be hope of quantifying downwind changes in the wet component of sulfur deposition with any degree of accuracy. At the same time, it must be pointed out that the air and precipitation monitoring network used in this study was not specifically designed to quantify the contribution of the Sudbury smelters. It is quite possible that a carefully-designed, source-oriented network would have a better chance of success. Furthermore, the use of inert tracers to assist in identifying the presence of air parcels which have passed over the sources of interest (e.g., in the present case, tracers released at Sudbury during both operating and shut-down periods) would be very useful in the sample stratification process, and the comparison of shut-down and operating period data.

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Table 1A

Mean Sulphate Loadings (mg/m^2) (Concentrations (mg/l))
due to the Sudbury Sector

	7/80 - 3/81	7/81 - 3/82	7/82 - 3/83
Dorset	2.2 (1.4)	6.0 (1.4)	3.5 (0.4)
Longwoods	7.8 (3.5)	9.9 (1.5)	5.6 (2.1)
Railton	2.3 (4.2)	7.5 (4.7)	9.2 (1.7)
Fernberg	no data	2.6 (0.8)	11.5 (0.5)
Chalk River	8.6 (3.5)	10.6 (1.8)	6.2 (1.3)
Kapuskasing	no data	no data	7.6 (3.1)

Table 1B

Mean Nitrate Loadings (mg/m^2) and
(Concentrations (mg/l)) due to the
Sudbury Sector

	7/80 - 3/81	7/81 - 3/82	7/82 - 3/83
Dorset	0.5 (0.4)	0.7 (0.1)	0.5 (0.1)
Longwoods	1.6 (1.0)	2.4 (0.5)	1.6 (0.6)
Railton	0.3 (1.1)	1.4 (0.7)	1.8 (0.3)
Fernberg	no data	0.4 (0.1)	1.1 (0.1)
Chalk River	1.0 (0.4)	3.9 (1.0)	0.6 (0.1)
Kapuskasing	no data	no data	1.1 (0.4)

Table 1C

Total Sudbury Sector Precipitation (mm) and
(Number of Events)

	7/80 - 3/81	7/81 - 3/82	7/82 - 3/83
Dorset	8 (6)	30 (4)	18 (8)
Longwoods	37 (14)	25 (10)	21 (9)
Railton	6 (6)	8 (4)	10 (2)
Fernberg	no data	9 (2)	23 (1)
Chalk River	26 (8)	12 (2)	25 (5)
Kapuskasing	no data	no data	24 (7)

TABLE 2

ESTIMATES (probably near Upper Limit) OF SUDBURY SMELTER CONTRIBUTION TO THE SO_4 WET DEPOSITION AT VARIOUS RECEPTORS IN ONTARIO (% of Total)

LOCATION	% SUDBURY SMELTER CONTRIBUTION	
	By classification according to synoptic meteorology and back trajectories	From simple trajectory analysis
Dorset	12	8
Railton	2	14
Longwoods	*	9
Chalk River	12	-

* Insufficient data for analysis

\- Trajectory data not available for all sectors

Table 3A
Mean Sulphur Dioxide Air Concentrations (ug/m^3)
Due to the Sudbury Sector

	Period 2 7/81-3/82			Period 3 7/82-3/83		
	No. of Events	Mean ug/m^3	S.D $ug/^3$	No. of Events	Mean ug/m^3	S.D. ug/m^3
Dorset	23	8.66	12.55	17	1.28	2.41
Longwoods	38	4.99	6.34	31	3.00	2.63
Railton	39	4.67	4.08	19	2.36	3.76
Fernberg	10	2.18	1.50	12	1.17	1.22
Chalk River	23	8.24	10.26	13	1.91	2.55
Kapuskasing	11	7.88	9.19	9	1.75	1.37

Table 3B
Mean Sulphate Air Concentrations (ug/m^3)
Due to the Sudbury Sector

	Period 2 7/81-3/82			Period 3 7/82-3/83		
	No. of Events	Mean ug/m^3	S.D $ug/^3$	No. of Events	Mean ug/m^3	S.D. ug/m^3
Dorset	22	2.28	1.74	18	0.70	0.72
Longwoods	39	2.61	2.22	33	3.03	2.92
Railton	40	1.52	1.13	19	1.31	0.99
Fernberg	10	0.73	0.70	13	1.09	0.78
Chalk River	23	1.95	1.93	18	0.80	0.62
Kapuskasing	11	4.37	5.64	9	1.90	2.14

Table 4

Mean Sulphur Dioxide Air Concentrations (ug/m^3) at Dorset

Sector Analysis - 6h Back Trajectories

Sudbury Sector: NW

Sector	Period 2 7/81 - 3/82 No. of Events	Mean ug/m^3	S.D ug/m^3	Period 3 7/82 - 3/83 No. of Events	Mean ug/m^3	S.D ug/m^3
N	46	3.69	3.97	31	2.74	3.09
NE	19	3.75	4.81	16	2.37	3.52
E	11	2.67	3.95	9	1.44	1.70
SE	25	4.32	7.15	22	4.17	4.22
S	36	10.86	8.75	27	6.33	6.70
SW	28	8.57	8.14	36	7.28	9.25
W	35	4.21	3.86	26	1.76	2.42
NW	23	8.66	12.55	17	1.28	2.41
Unknown	23	4.14	4.94	23	2.64	5.15
Total	246			207		
Average		5.90	7.40		3.81	5.76

TABLE 5

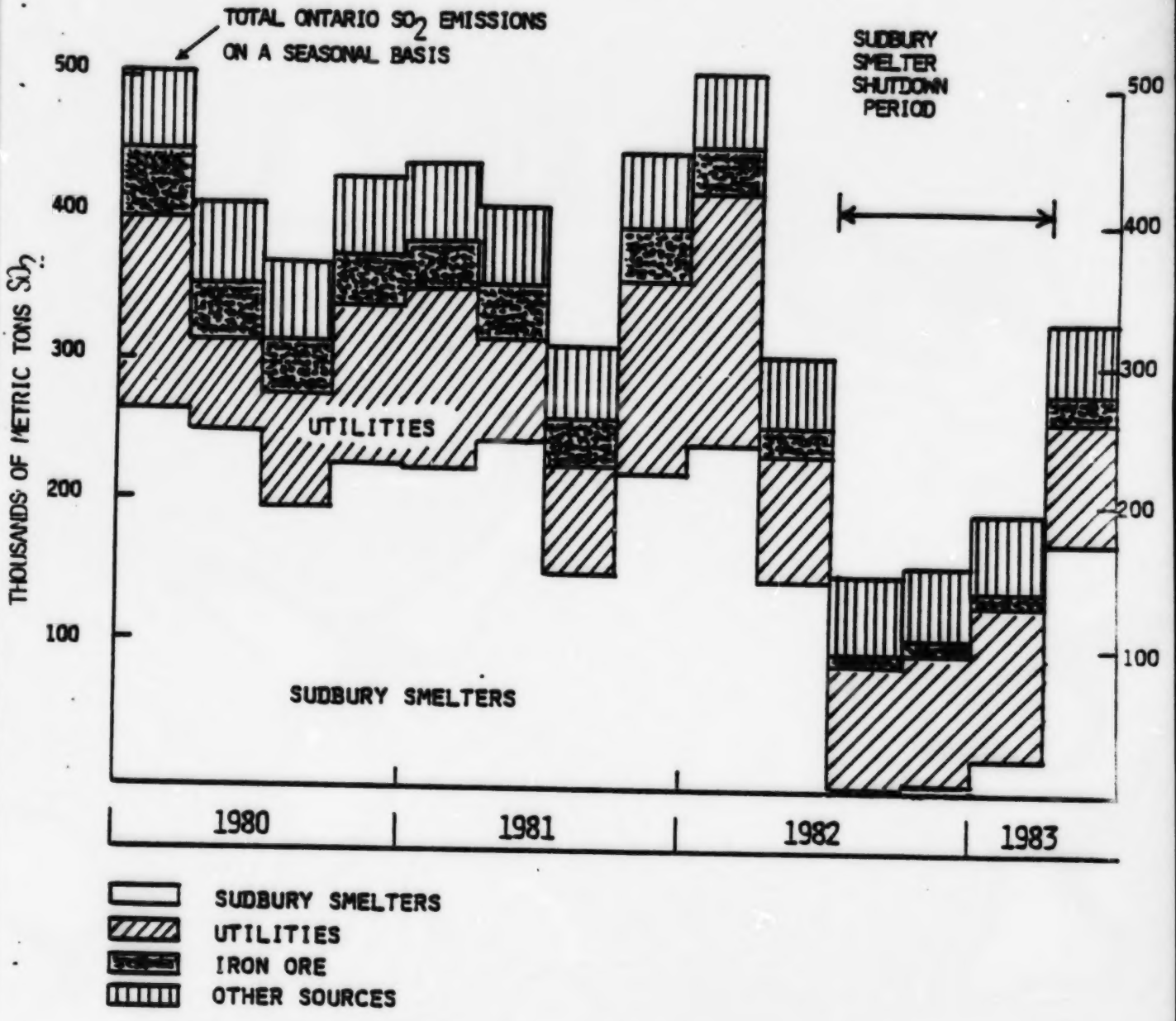
ESTIMATES OF SMELTER CONTRIBUTION (% of the Total)

TO SO_2 AND SO_4 DRY DEPOSITION IN ONTARIO

LOCATION	PARAMETER	% SMELTER CONTRIBUTION	
		Trajectory	Trajectory/ Synoptic Meteorology
Dorset	SO_2	11	<37
	SO_4	4	<18
Railton	SO_2	7	<27
	SO_4	4	**
Longwoods	SO_2	3	<5
	SO_4	*	**
Fernberg	SO_2	*	<4
	SO_4	*	**
Kapuskasing	SO_2	18	<47
	SO_2	7	<46
Chalk River	SO_2	6	<26
	SO_4	6	<20

* Too small to quantify

** Insufficient data for analysis



SEASONAL VARIATION IN THE SO_2 EMISSIONS IN ONTARIO
FOR THE PERIOD JAN. 1980 - JUN. 1983

FIGURE 1

FIGURE 2 : STATION LOCATION MAP

CUMULATIVE PRECIPITATION

MONITORING NETWORK

1 - COLCHESTER
2 - MERLIN
3 - PORT STANLEY
4 - WILKESPORT
5 - ALVINSTON
6 - HURON PARK
7 - WATERLOO
8 - PALMERSTON
9 - SHALLOW LAKE
10 - MILTON
11 - UXBRIDGE
12 - COLDWATER
13 - CAMPBELLFORD
14 - KALADAR
15 - SMITH'S FALLS
16 - DALHOUSIE MILLS
17 - GOLDEN LAKE
18 - WILBERFORCE
19 - WHITNEY
20 - DORSET
21 - MCKELLAR
22 - MATTAWA
23 - KILLARNEY
24 - BEAR ISLAND
25 - GOMMANDA
26 - RAMSEY
27 - MOONBEAM
28 - ATTAWAPISKAT
29 - WINISK
30 - MAKINA
31 - ORRION
32 - QUETICO CENTRE
33 - LAC LA CROIX
34 - EXP. LAKES AREA
35 - EAR FALLS
36 - PICKLE LAKE

Figure 3

STATION LOCATION MAP

FIGURE 4 : BAR CHART OF MEANS ($SO_4^{=}$)

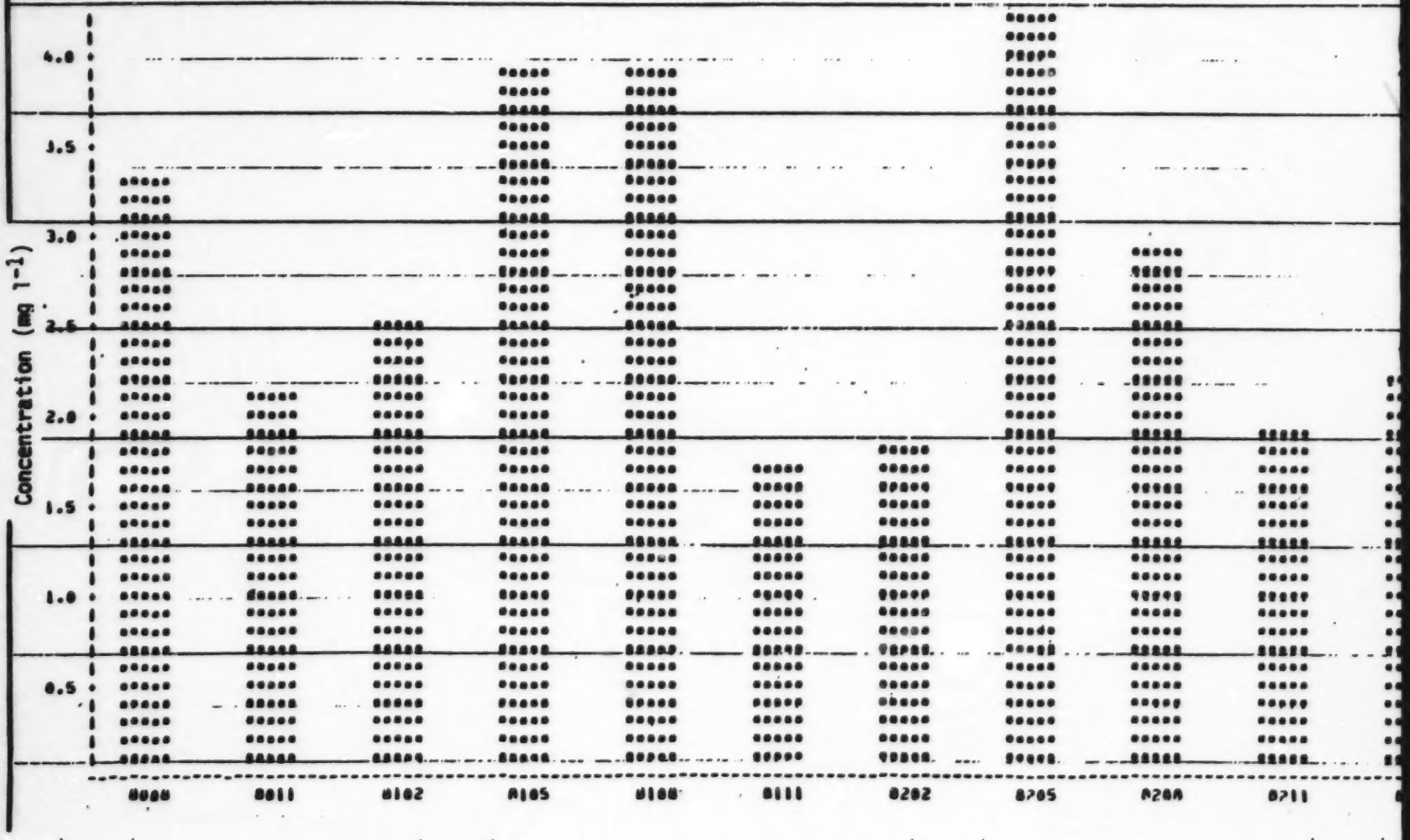


FIGURE 5 : BAR CHART OF MEANS (Cu)

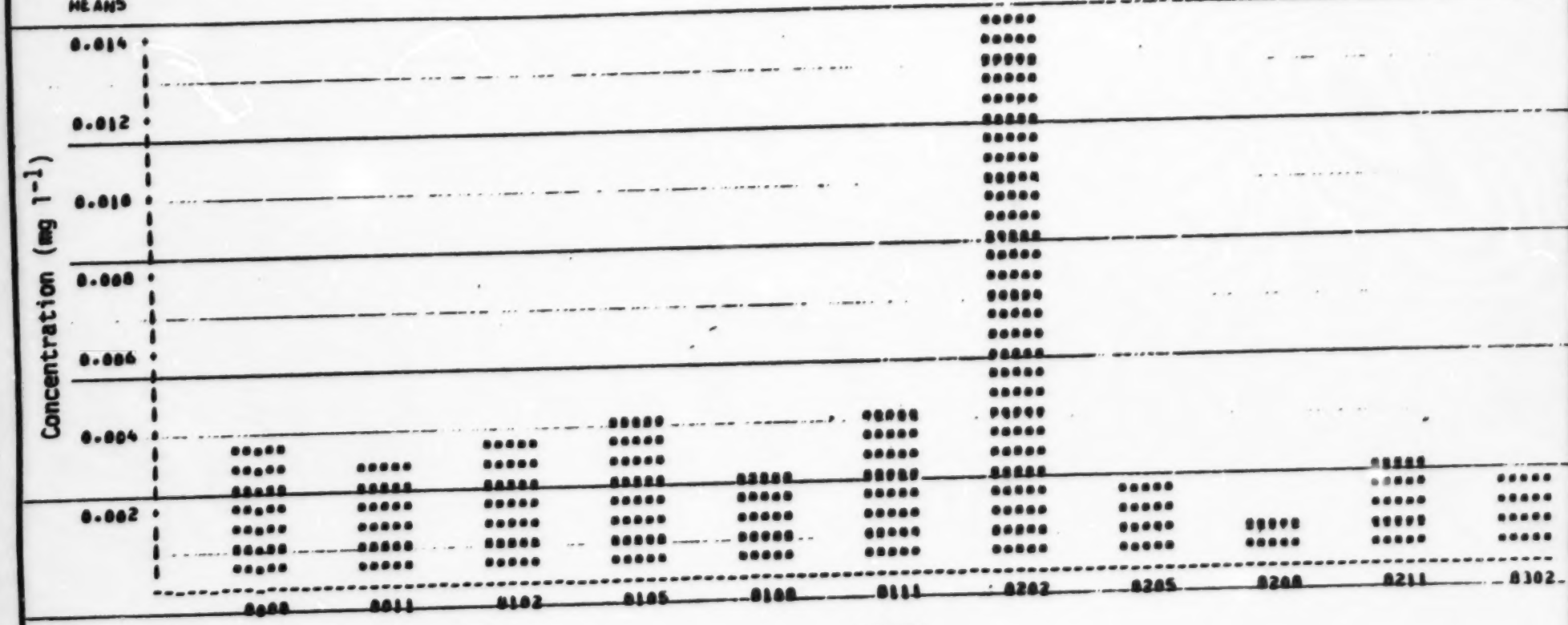
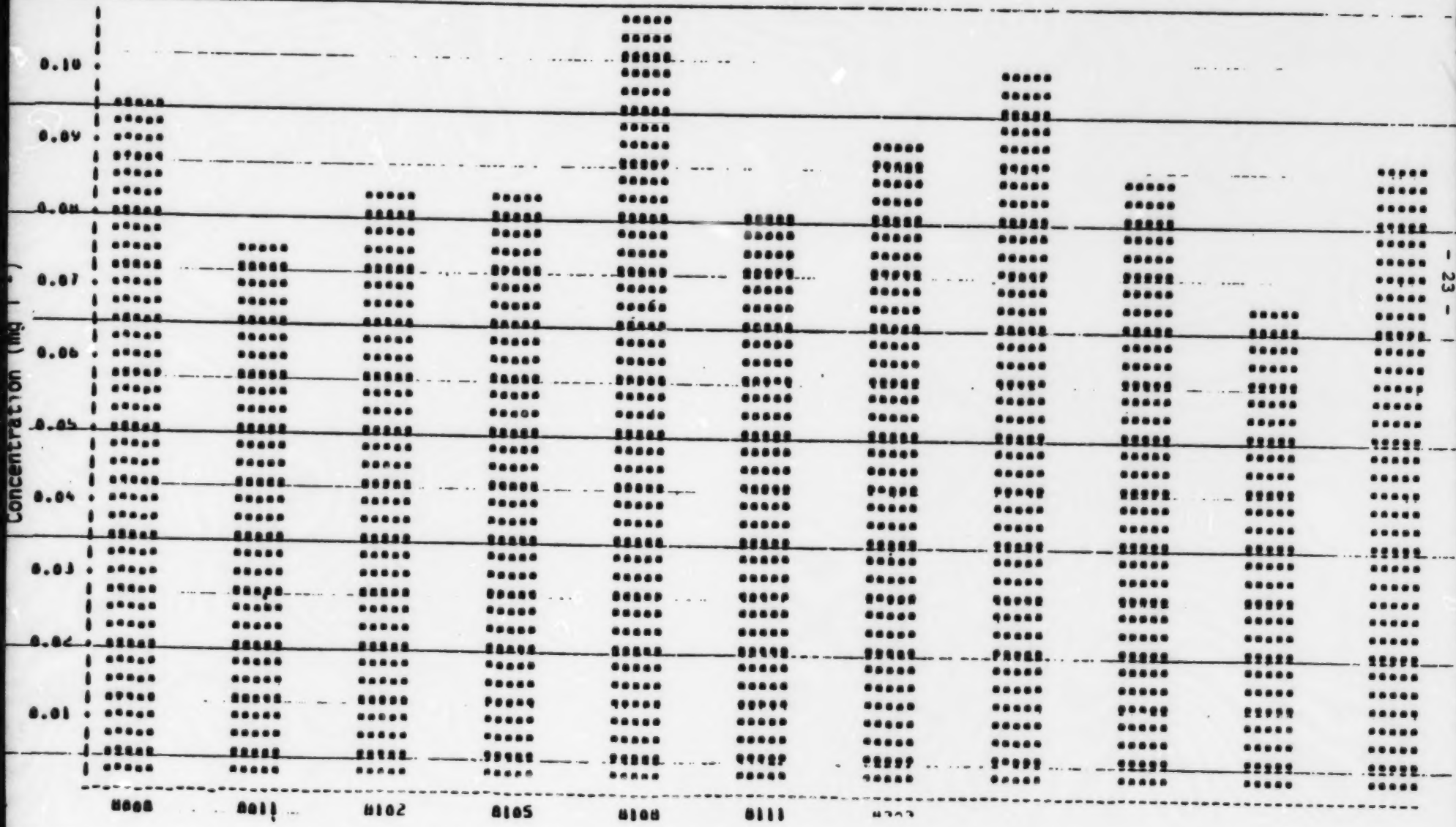


FIGURE 6 BAR CHART OF MEAN2 (H_t^+)



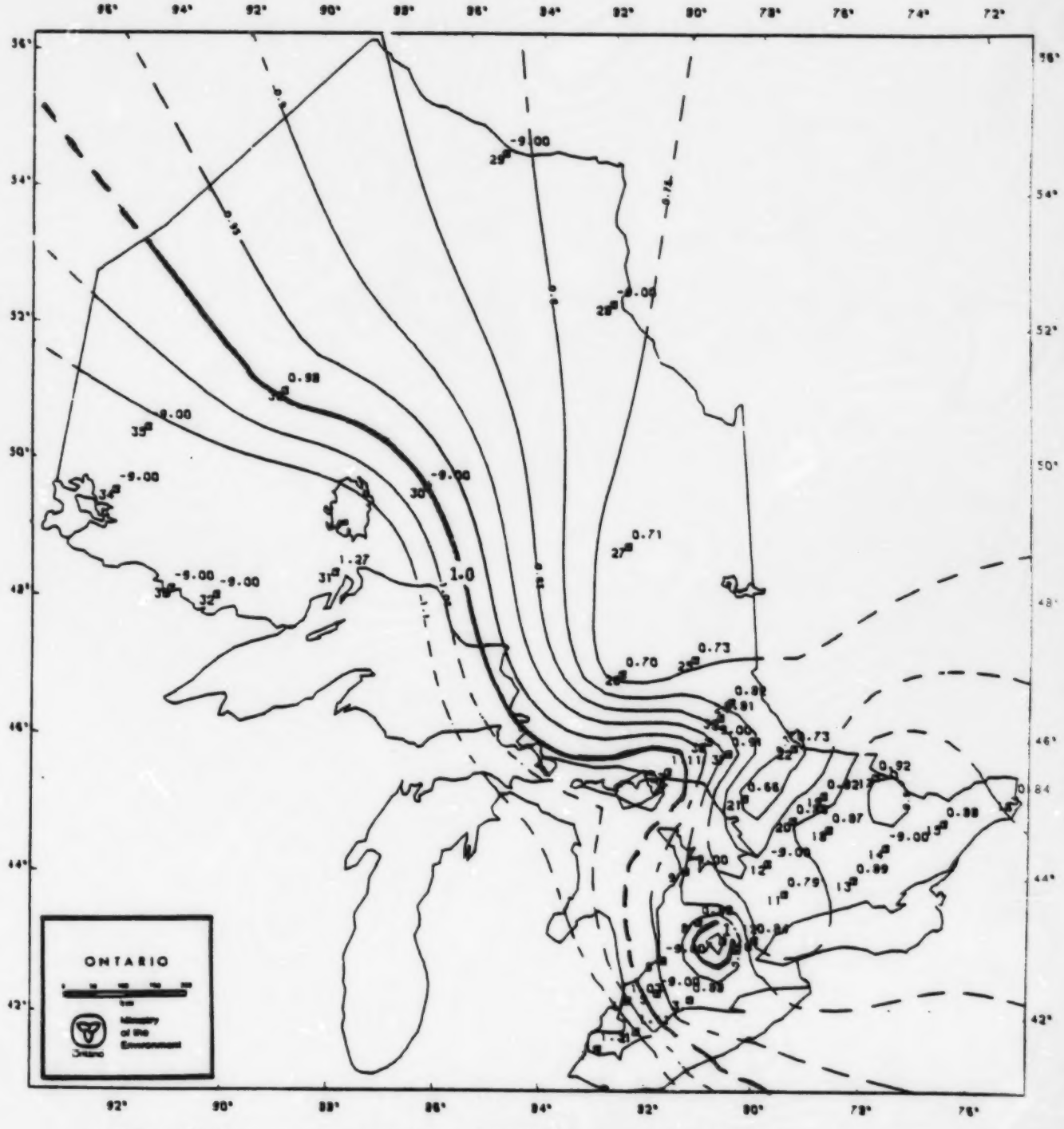


FIGURE 7: RATIO OF SO4 CONCENTRATION BETWEEN 82-83 AND 80-81

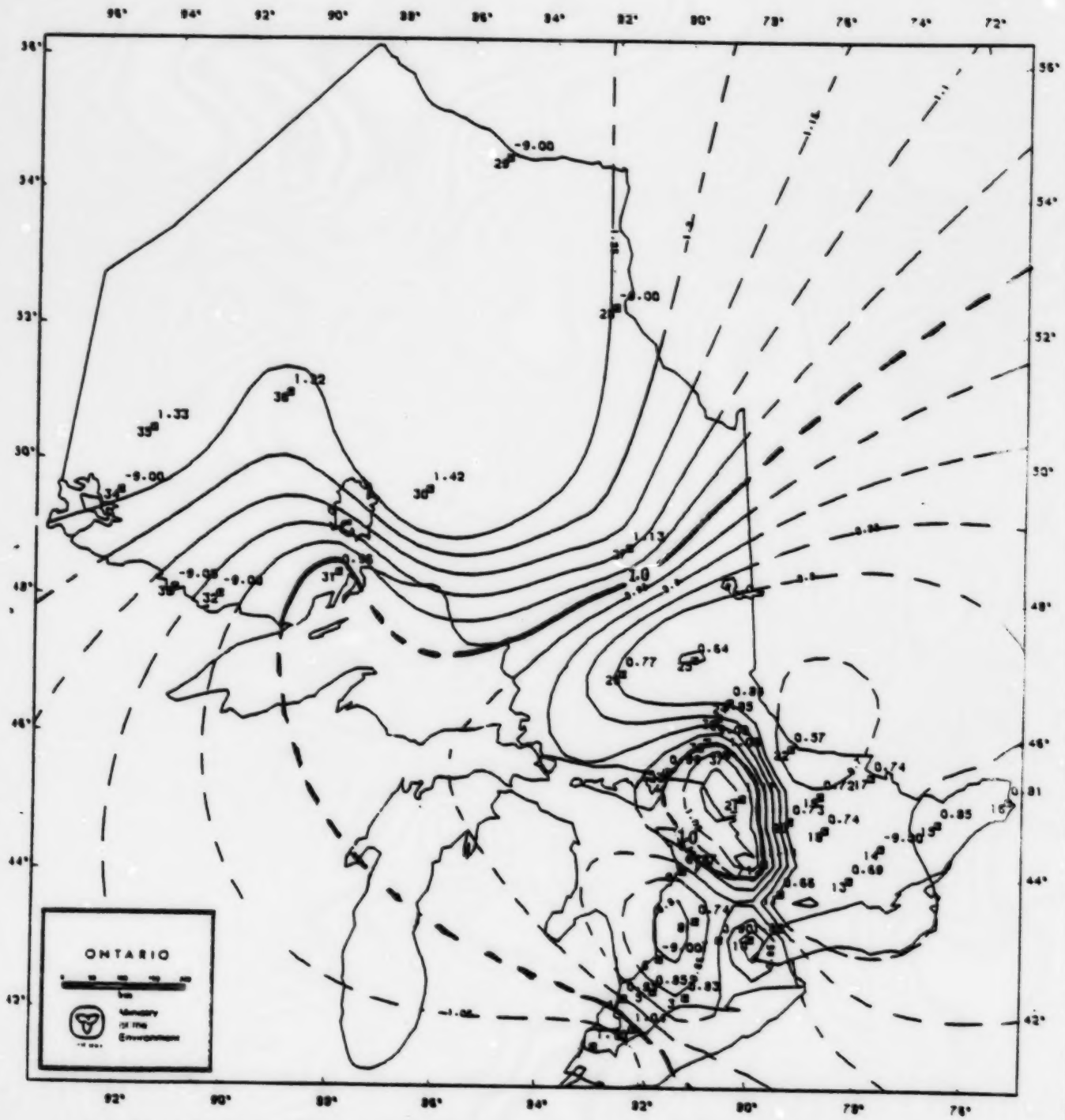


FIGURE 8: RATIO OF SO4 CONCENTRATION BETWEEN 82-83 AND 81-82

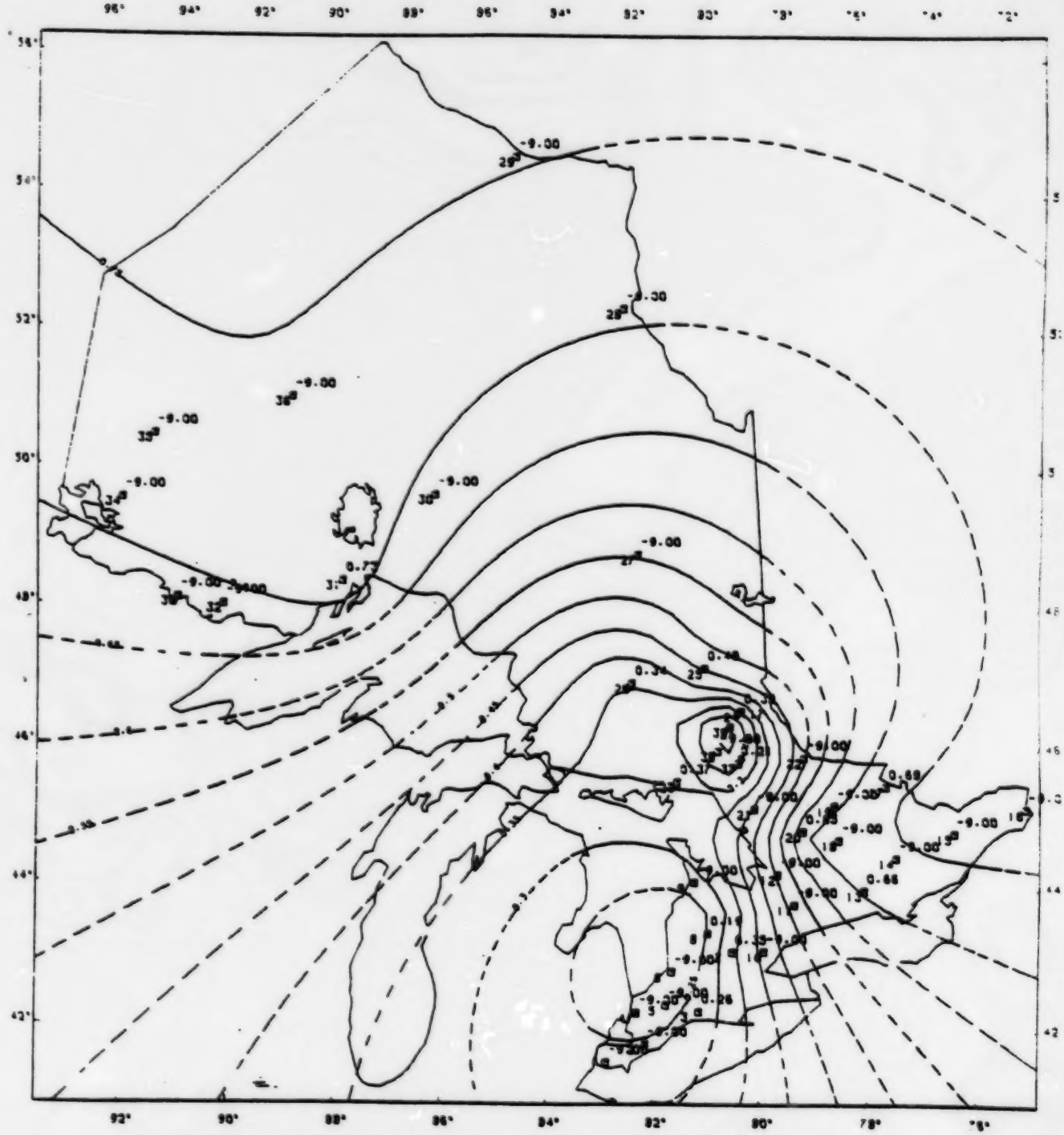


FIGURE 9. RATIO OF CU CONCENTRATION BETWEEN 82-83 AND 80-81

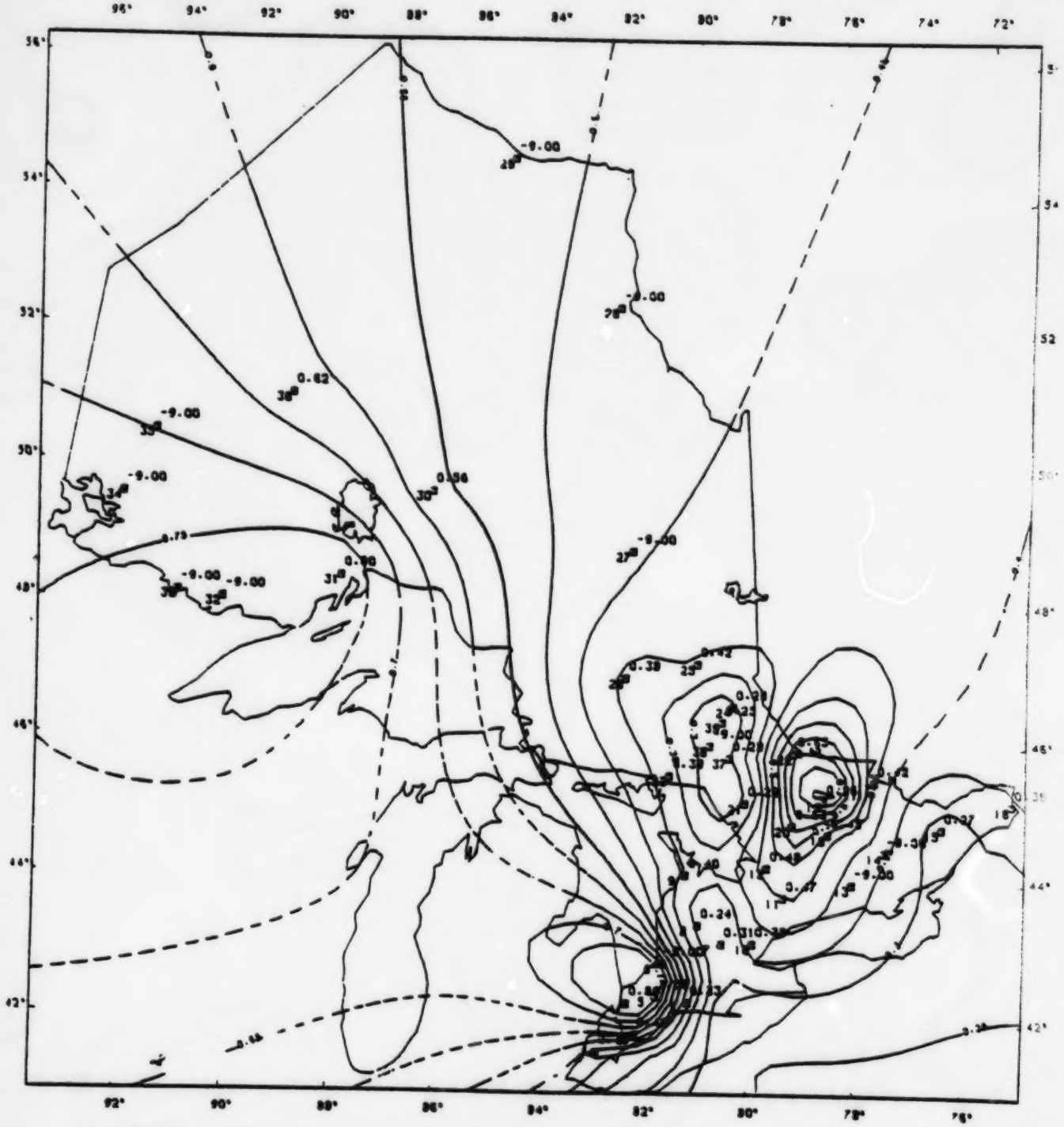


FIGURE 10 RATIO OF CU CONCENTRATION BETWEEN 82-83 AND 81-82

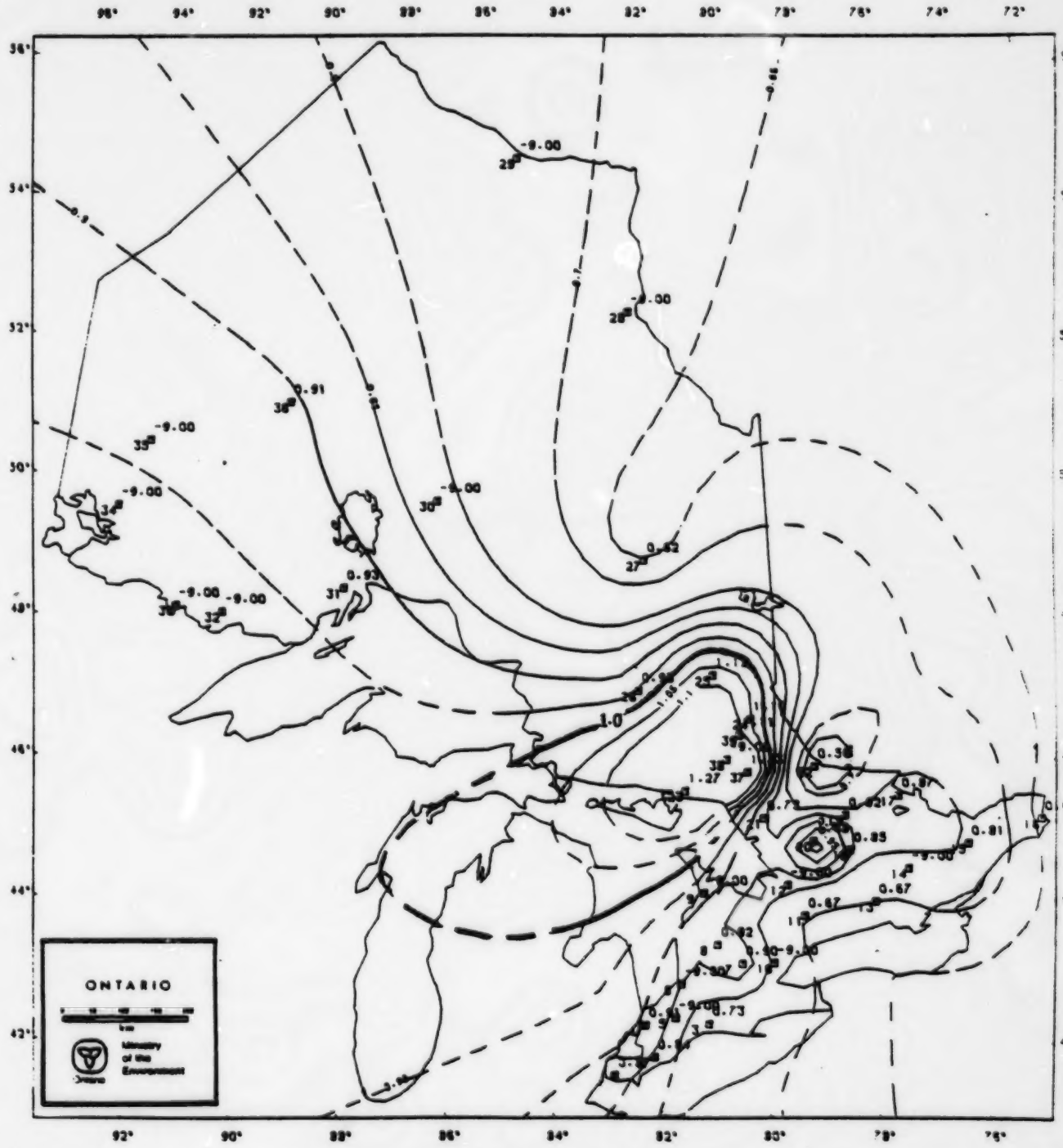


FIGURE 11: RATIO OF N-NO3 CONCENTRATION BETWEEN 82-83 AND 80-81

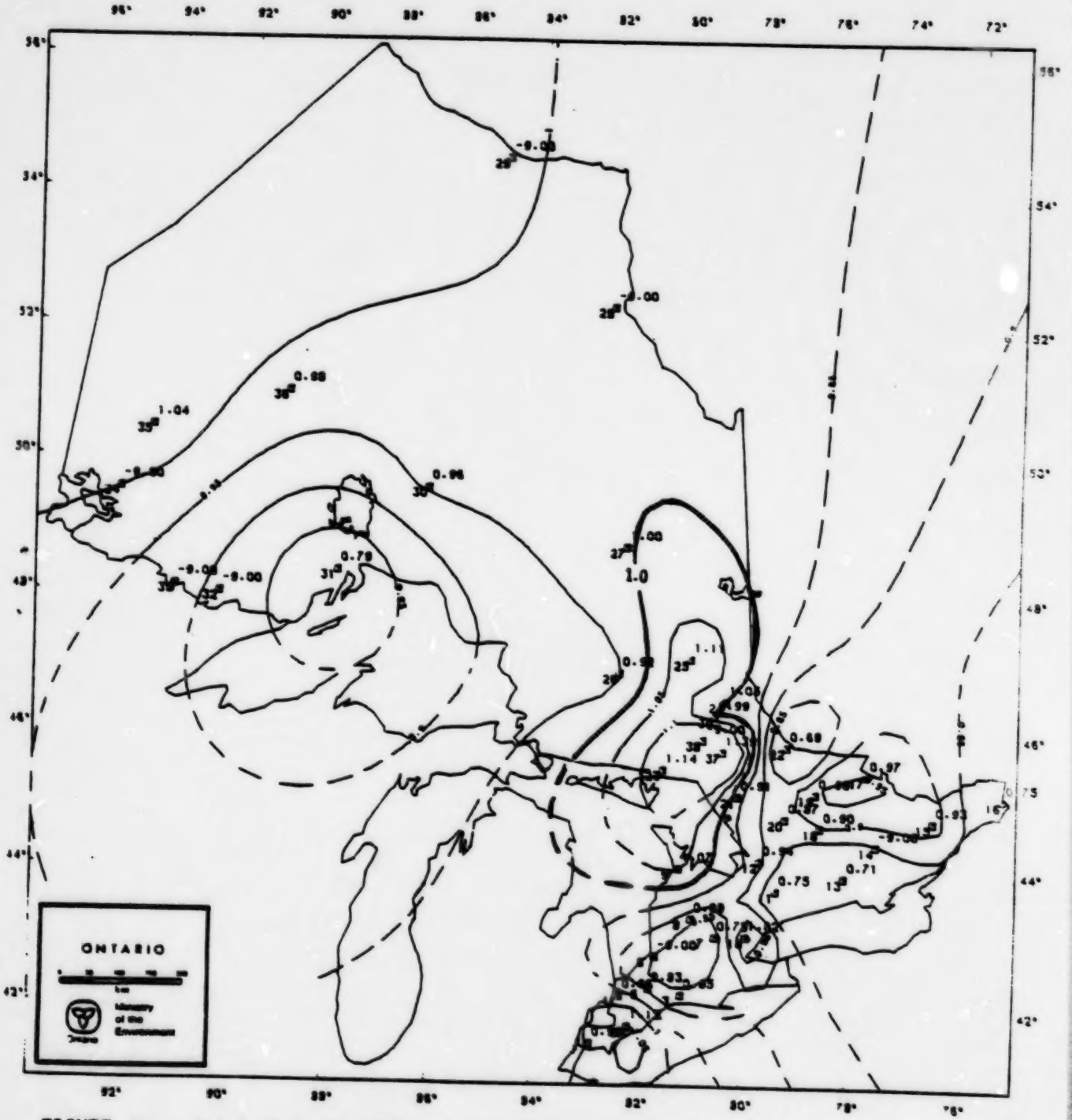


FIGURE 12: RATIO OF N-NO3 CONCENTRATION BETWEEN 82-83 AND 81-82

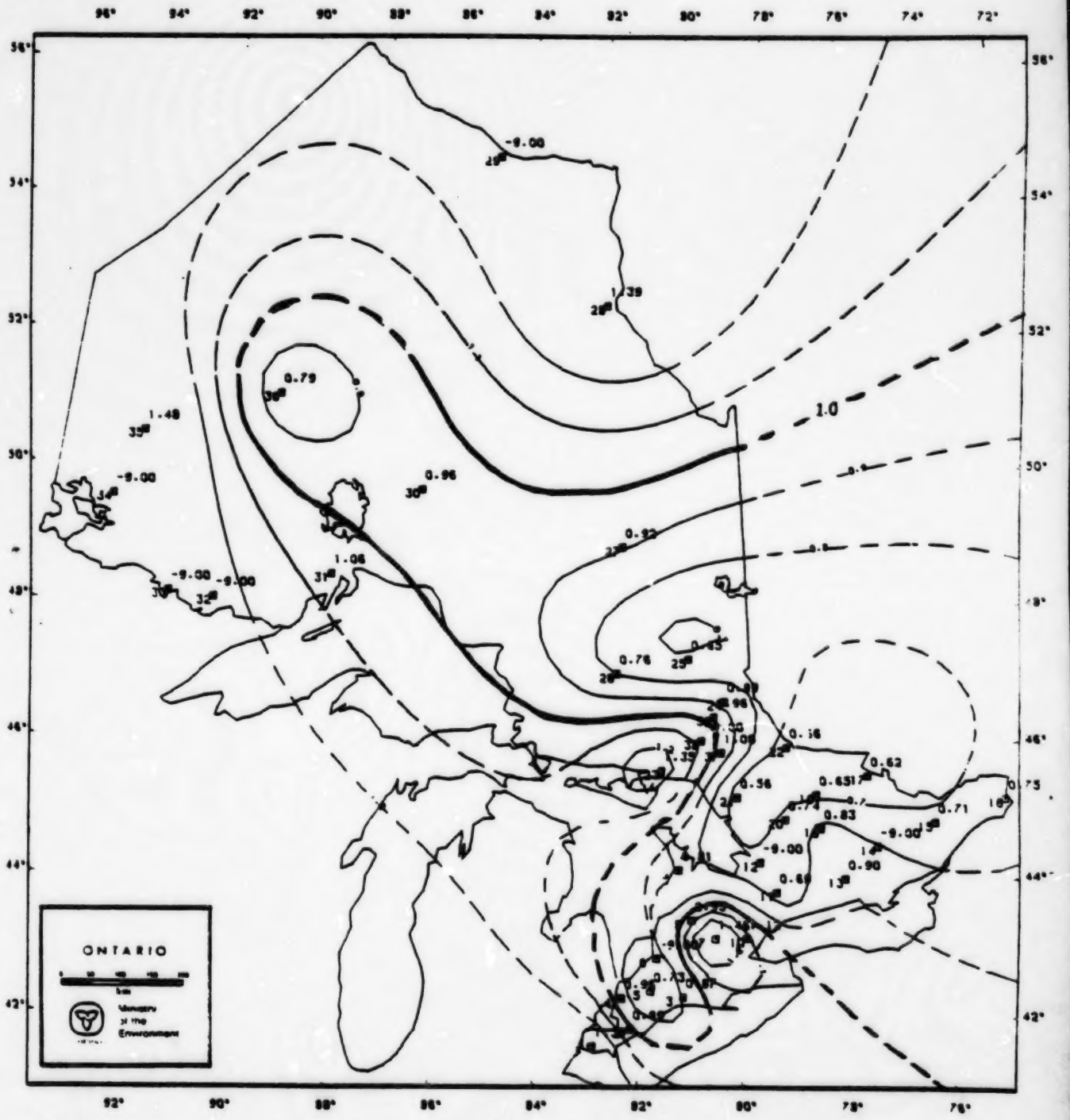


FIGURE 13: RATIO OF SO4 DEPOSITION BETWEEN 82-83 AND 80-81

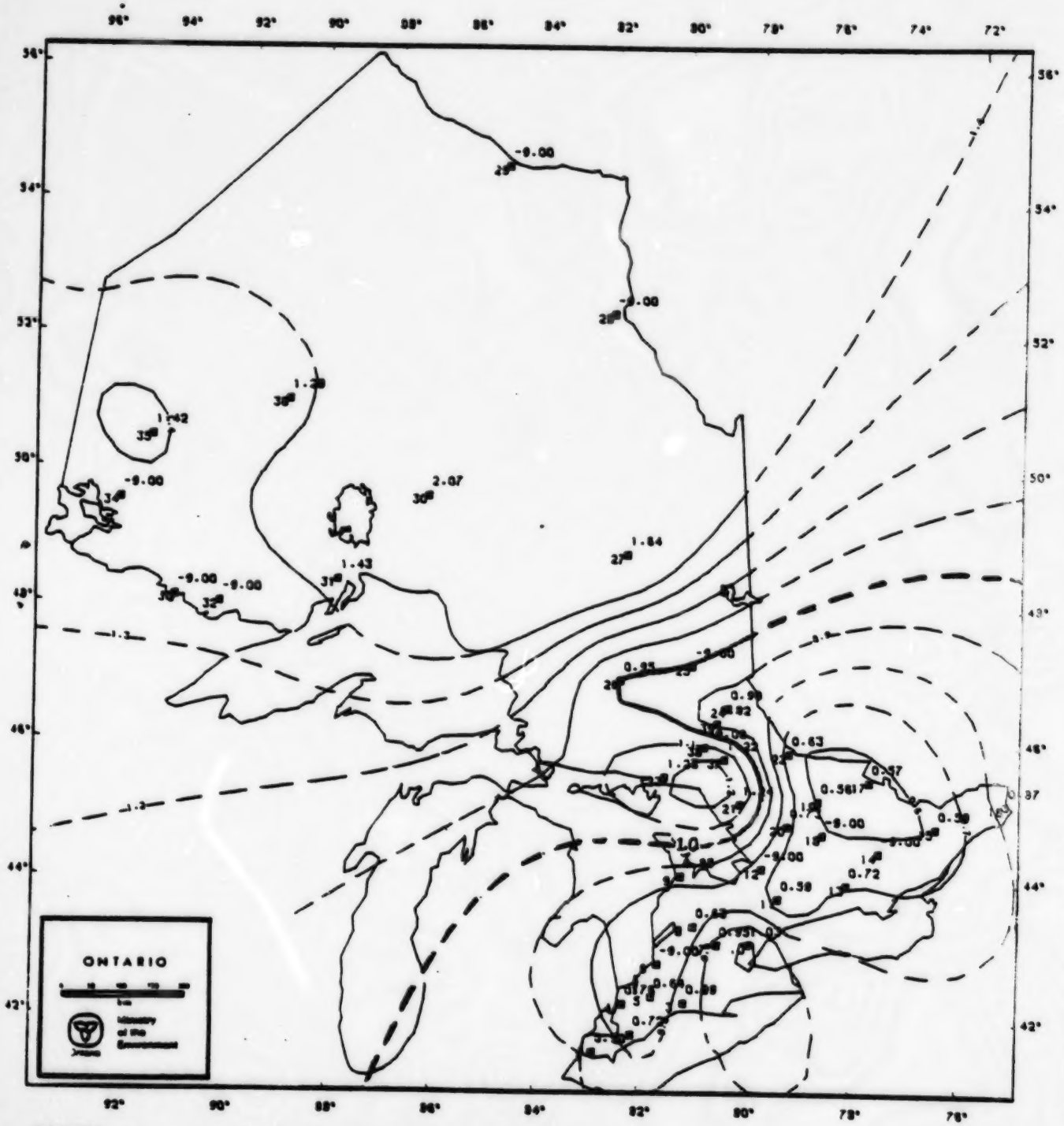


FIGURE 14: RATIO OF SO4 DEPOSITION BETWEEN 82-83 AND 81-82

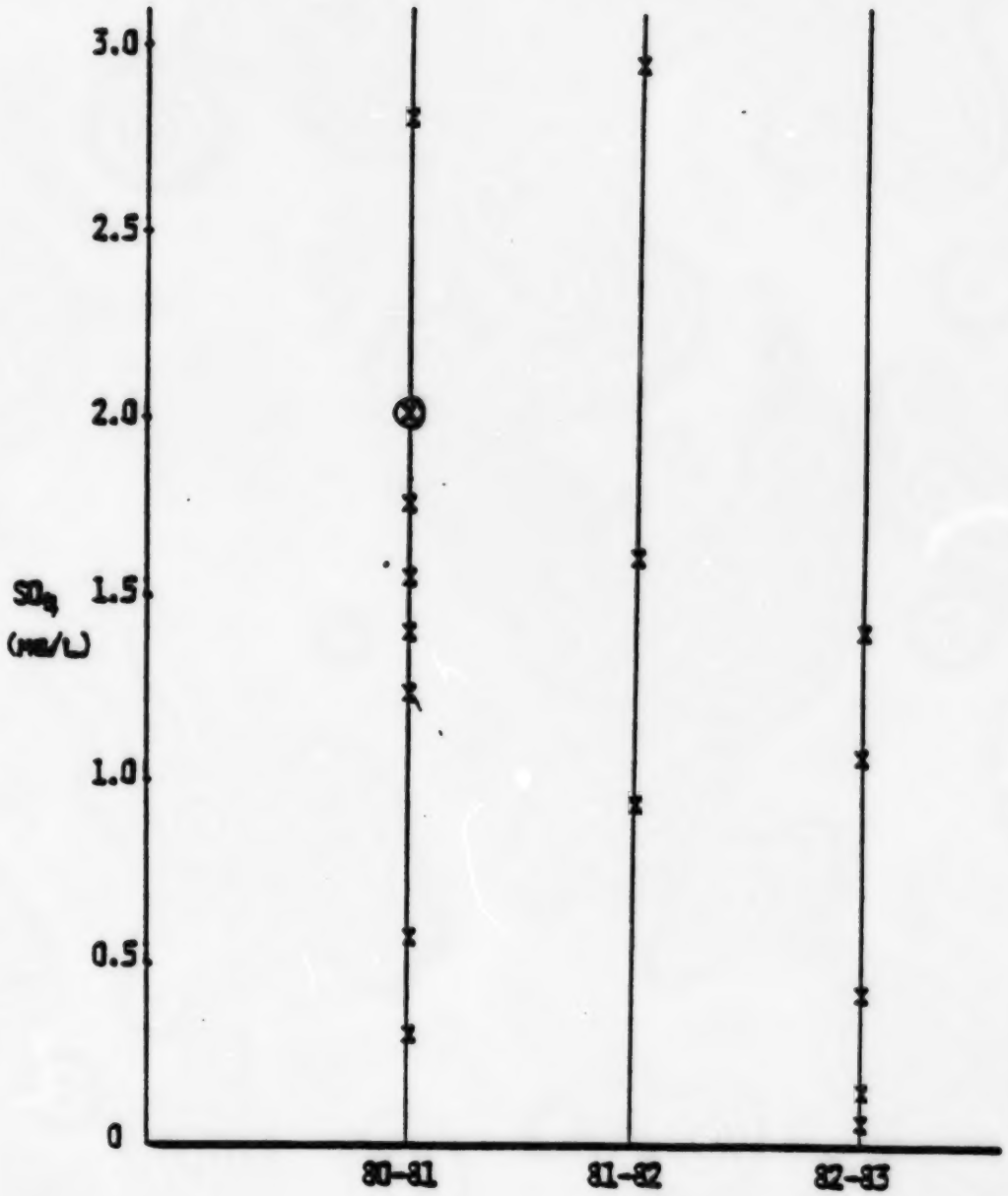


Figure 15 SULFATE PRECIPITATION CONCENTRATION OF THE STRATIFIED SAMPLES AT DORSET
(⊗ DENOTES 2 POINTS)

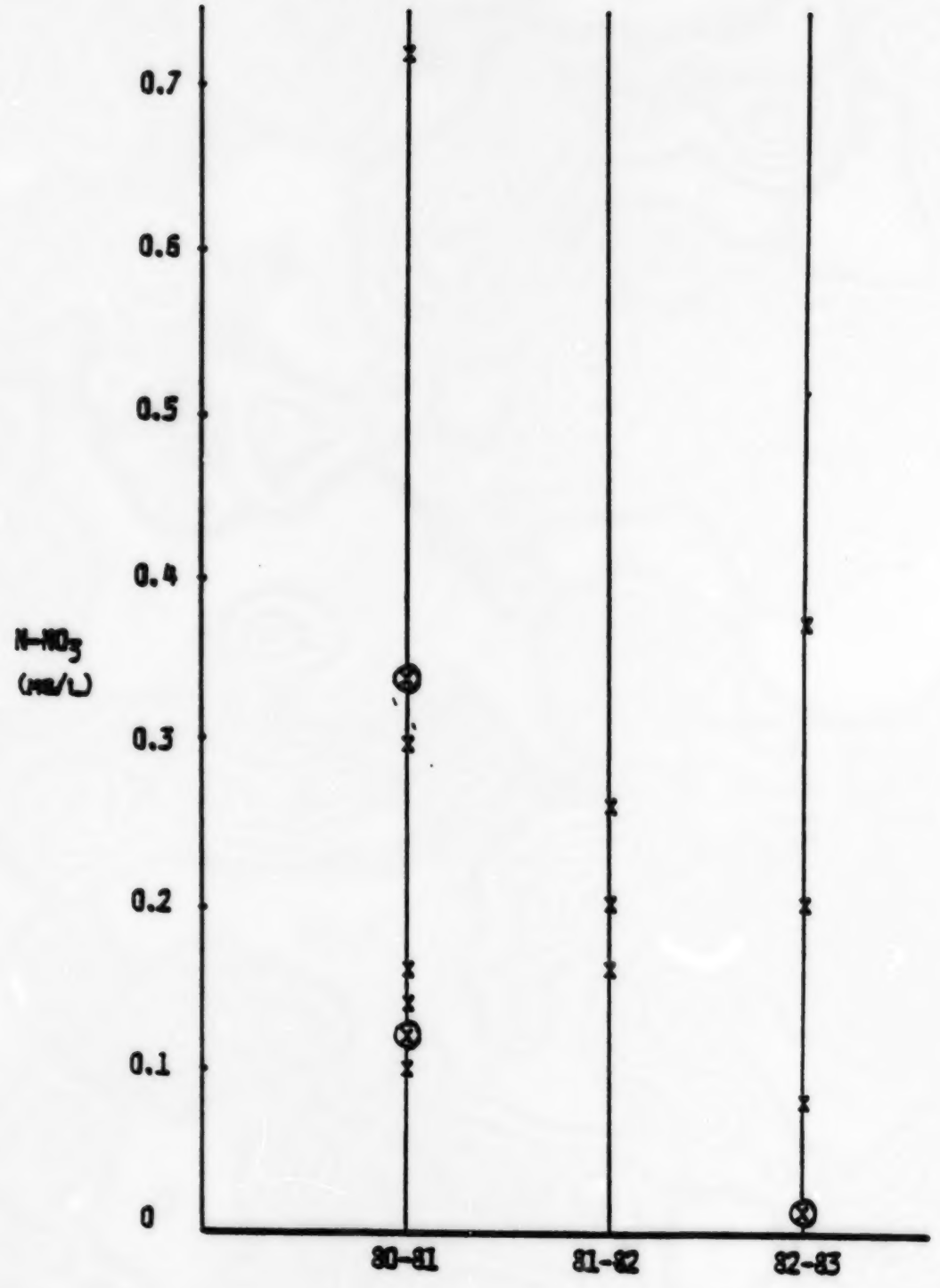


Figure 16 NITRATE PRECIPITATION CONCENTRATION OF THE STRATIFIED SAMPLES AT DORSET

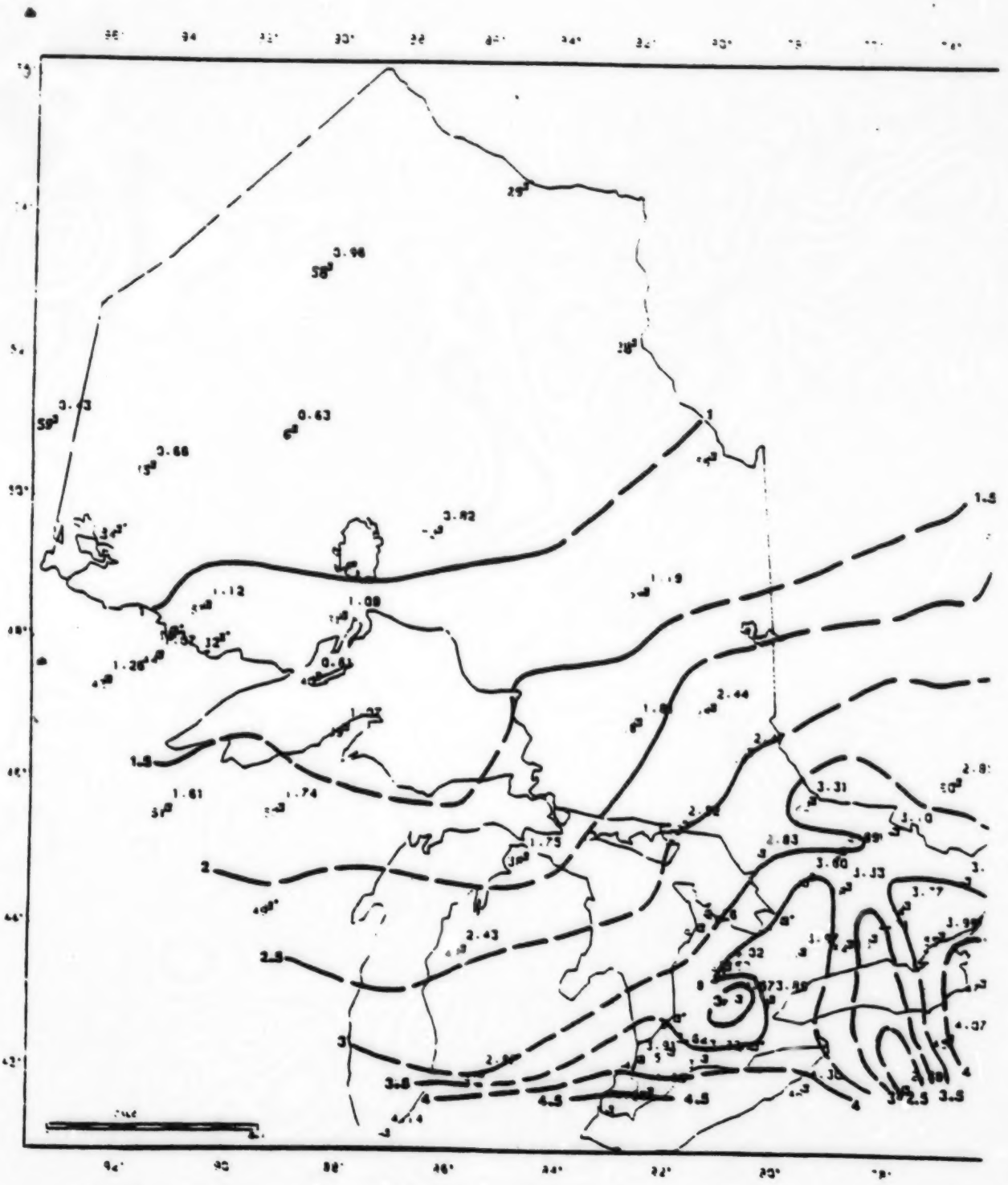
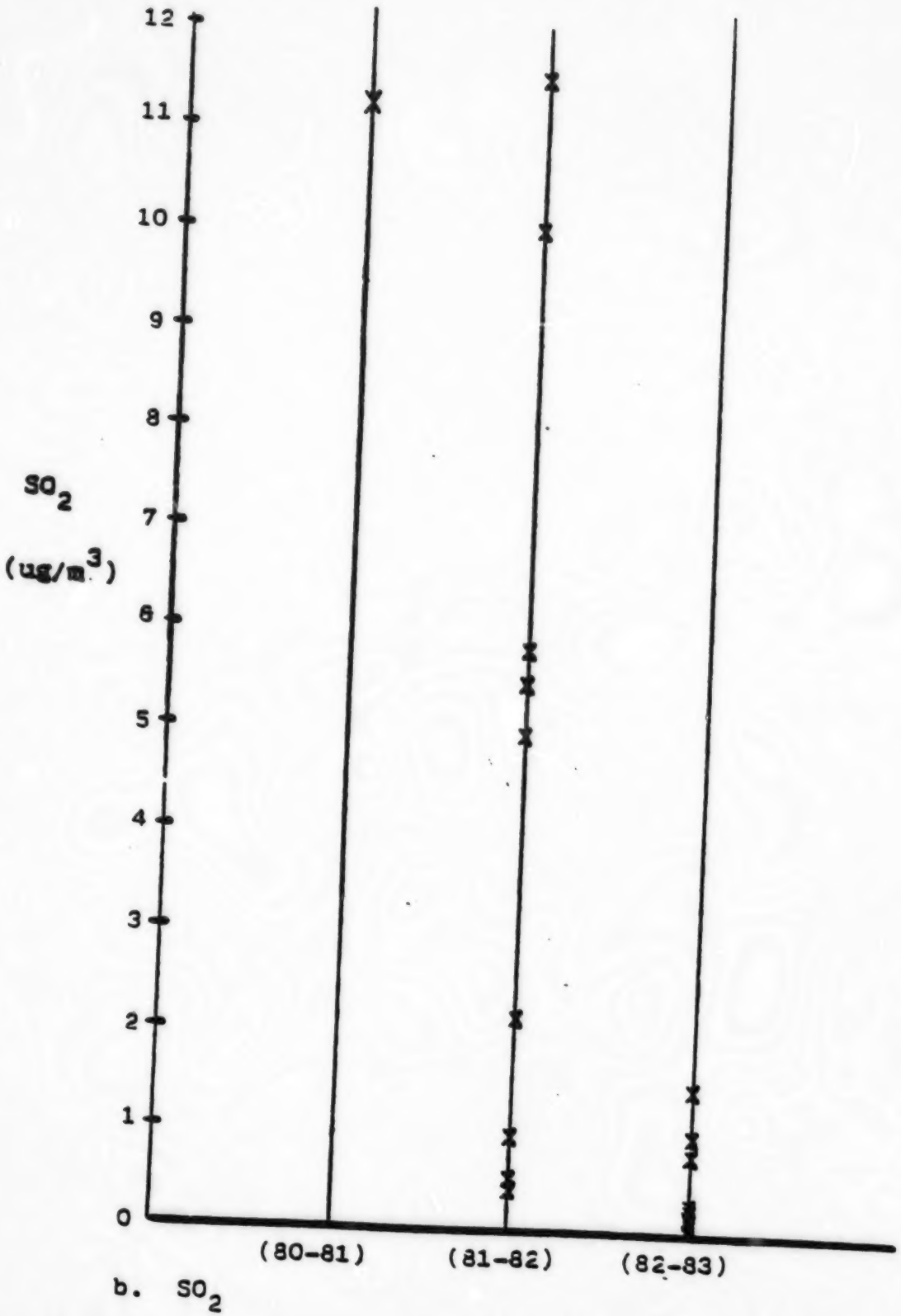


FIGURE 17 ANNUAL DEPOSITION(G/M**2) OF SO4 - 1981



b. SO_2

Figure 18 GROUND-LEVEL AIR SO_2 CONCENTRATION OF THE STRATIFIED SAMPLES AT DORSET.